Climatic and Anthropogenic Impacts on the Variability of Water Resources
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Climatic and Human Influences on Water Resources in Low Atolls

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Abstract. Low, small islands have water supply problems amongst the most critical in the world. Fresh groundwater, the major source of water in many atolls, is vulnerable to natural and human-induced changes. Storm surges, droughts and over-extraction cause seawater intrusion. Settlements and agricultural activities can rapidly pollute shallow groundwaters. Limited land areas restrict freshwater quantities, which are especially vulnerable during frequent ENSO-related droughts. Demand for freshwater is increasing due to population growth and urbanisation. Water use for traditional crops often competes with water supplies for communities. This paper analyses the impact of frequent severe droughts on the quality and quantity of fresh groundwater in a low, atoll, Tarawa, in the Republic of Kiribati. We also examine the impacts of groundwater harvesting on traditional subsistence crops such as coconuts and of landuse on water quality. Strategies for reducing risks from climate variations and human impacts and increasing resilience are discussed.

Keywords: Small islands; freshwater supplies; ENSO; drought; pollution; climate variation; risk, adaptation, and resilience.

INTRODUCTION

The Barbados Conference on the Sustainable Development of Small Island States in 1994 focussed world-attention on their fragility and vulnerability. This vulnerability is a product of their remoteness, small size, rapid population growth, restricted capacity and resources and sensitivity to climate variability. Low Gross Domestic Product, limited opportunities and increasing urbanisation are straining traditional support mechanisms (Ward, 1999) and customary traditional approaches to hazard reduction. There are about 8,000 inhabited small tropical islands in the Pacific, Indian and Atlantic Oceans. Many, formed as sand cays, coral atolls or elevated limestone islands, are very small islands, with land areas less than 100 km^2 or with maximum widths less than 3 km. In these islands, surface water resources are usually non-existent because of large soil permeabilities and fresh groundwater resources can be very limited because of restricted land areas and high regolith permeabilities (UNESCO, 1991).

Small island countries face water problems that are amongst the most critical in the world (Carpenter *et al.*, 2002). This is especially so in urban and peri-urban low coral atoll communities (Ward, 1999), on which we concentrate here. Storage of freshwater in atolls to reduce risks during dry periods is constrained by very small land areas, atoll aquifer geology, pressures of human settlements and increasing demand, agricultural activities and waste disposal. Frequent droughts, climate variability and seawater inundation during storms as well as conflicts over traditional resource rights and the demands or urbanised societies add to the difficulties (Falkland, 2002, White *et al.*, 1999b).

The atolls that are most vulnerable to climate variations and human impacts are those with densely populated low islands atolls that rely solely either on thin fresh groundwater lenses for water supplies or those where rainwater is the only water source. In both, limitations in water storage, increase the risk of shortages during dry times. In the past, normal climatic variability in some atoll nations has resulted in declarations of states of emergency and in the evacuation of island populations. In groundwater-dependent atolls traditional, subsistence crops, such as coconuts, swamp taro, breadfruit and pandanus, compete with humans for freshwater (White *et al.,* 2002). Expanding urban atoll communities have the potential to rapidly pollute groundwaters so that water-borne diseases are often endemic. As a consequence, protection of human health is of paramount concern in water supply systems. In populous atolls, land is scarce and the potential to increase wealth through irrigated crops or tourism is restricted.

In this paper we examine the impact of ENSO-related droughts on freshwater availability and water quality in a densely populated central Pacific atoll, Tarawa, Republic of Kiribati. We explore the impacts of human settlements on water supply and its quality. Finally we look strategies to protect water resources and reduce risks.

STUDY LOCATION

Table 1 lists the relevant attributes of the central Pacific nation of Kiribati. The country has three key features: the predominance of very low coral atolls; the extent of available freshwater supplies are unknown; and, in its population centres, demand for equals or exceeds supply. In 2000, Tarawa atoll (Fig 1), the capital and population centre of the Republic of Kiribati, had a population of 36,227 people. Most live in South Tarawa between the islands of Betio and Buota (Fig1). North Tarawa is rural with low population density. By 2010 the population of Tarawa is expected to exceed 49,000 with population densities as high as 10,000/km^2.

In South Tarawa, water supply for the reticulation system is extracted using horizontal infiltration galleries from large freshwater lenses in groundwater reserves on Bonriki (Fig 2) and Buota islands in the southeastern corner of the atoll. It is then reticulated along the populous South Tarawa as far as the port of Betio in the west. Infiltration galleries minimise the risk of saline intrusion during pumping. Almost all households supplement that supply using dug domestic wells with water of variable quality in both salinity and in contaminants. Some also use rainwater harvesting to supplement supplies.

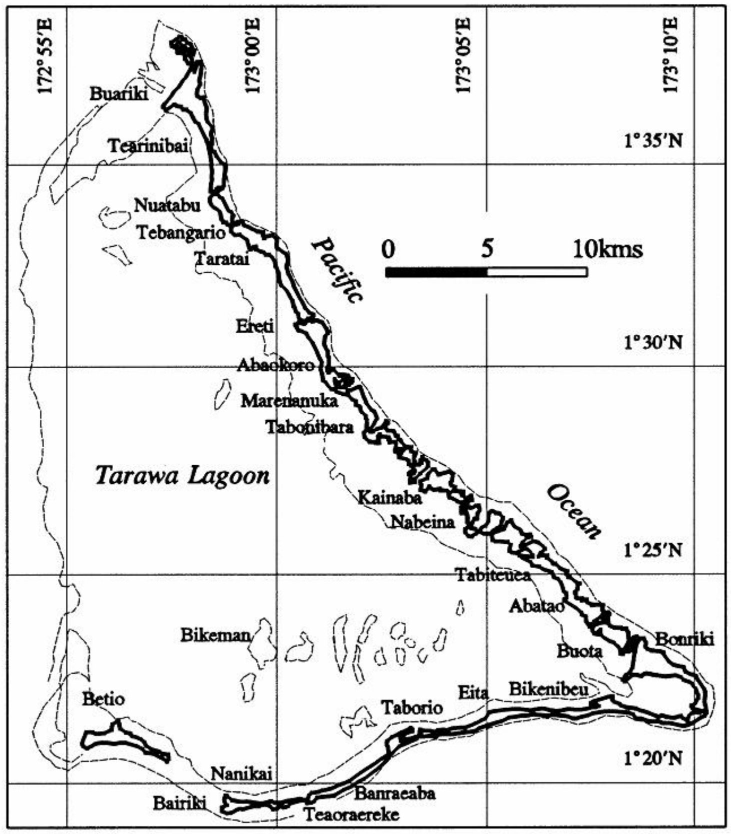

Fig.1 Tarawa atoll, capital of the Republic of Kiribati.

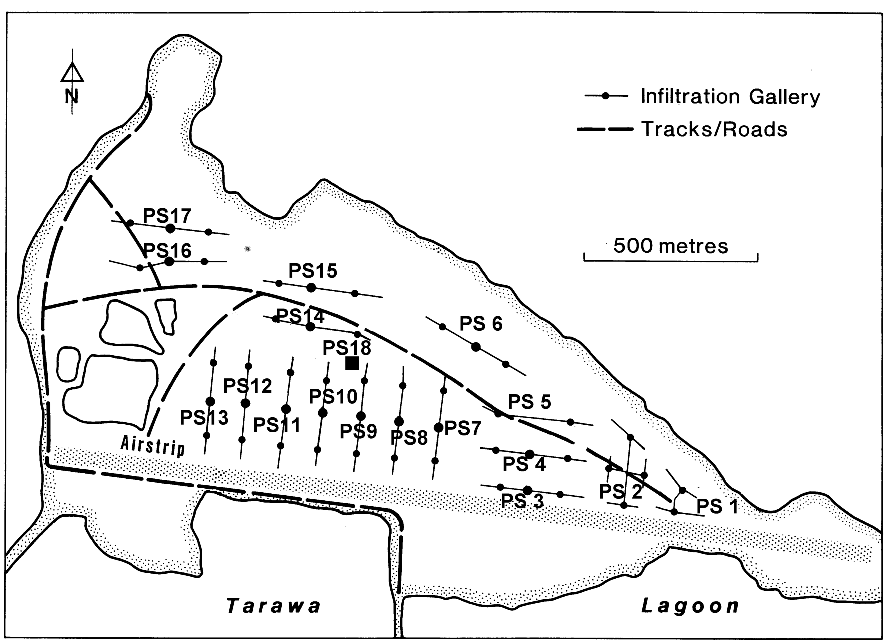

Fig. 2 Distribution of 18 horizontal infiltration gallery pumping stations on Bonriki island.

Table 2. Summary of the key features of Kiribati

Property	Value
Geographic location[1]	1º 25´ N 173º E (Tarawa)
Composition [1]	32 coral atolls, 1 raised coral island (Banaba)
Land area (km^2) [1]	811
Length of coast (km) [1]	1,143
Length of coast/land area (km^{-1}) [1]	1.41
Highest elevation (m above mean sea level)[1]	81 (Banaba)
Fraction of land elevation< 10 m above msl (%) [2,]	99
Climate [1]	Tropical
Cyclones	No
Mean annual rainfall (P mm) [4]	2048 (Tarawa)
Coefficient of variation annual rainfall (CV, %) [3]	48 (Tarawa)
Annual potential evaporation (E mm) [3]	1795 (Tarawa)
Aridity ratio = E/P	0.88 (Tarawa)
Principal water sources [4]	Reticulated groundwater (South Tarawa) Private groundwater wells Public groundwater wells & galleries (outer islands) Private rainwater tanks Desalination[*] Seawater (washing, toilet flushing)
Estimated per capita demand freshwater (L/cap/day) [4]	50 (Tarawa)
Estimated sustainable yield freshwater (L/cap/day) [5]	49 (Tarawa reticulation system)[†]
Agencies responsible for water supply	PUB (South Tarawa) MPWU (outer islands) Households
Population [1]	103,092 (est. Jul 2005)
Population growth rate (%) [1]	2.25 (est. 2005)
Mean population density (cap/km^2)	127
Environmental Vulnerability Index (EVI)[2]	3.70
EVI ranking (out of 235 countries) [6]	34/235

[1]CIA The World Factbook (2005), [2]Pratt and Mitchell (2003), [3]Falkland and Woodroffe (1997)
[4]Fakland (2005), [5]Alam *et al.*(2002), [6]Kali *et al.* (2003)
[*]Desalination plants are currently inoperative
[†] Excludes use of private wells or raintanks

Although South Tarawa has an average annual rainfall of 2048 mm, it has a high coefficient of variability (CV) of 0.48 (Table 1) because of the influence of the migrating Pacific warm pool and has experienced droughts as long as 30 months. In response to the 1998-2001 drought, reverse osmosis desalination units were installed in South Tarawa. These have subsequently failed or are currently not operating. Difficulties in maintaining production from desalination plants in common in many small island countries.

RELATION BETWEEN RAINFALL, ENSO EVENTS AND GROUNDWATER

Rainfall

Annual rainfall in Tarawa (Betio) is strongly negatively correlated with the Southern Oscillation Index, SOI (correlation coefficient -0.78). High rainfalls occur during El Niño events and low rainfalls during La Niña episodes. This strong correlation gives rise to frequent severe droughts (approximate frequency 6-7 years) that have major impacts on the availability of freshwater in Tarawa (Falkland, 1992; White *et al.,* 1999a). Fig 3 shows the strong negative relationship between 12 mth running totals of rainfall at Betio (Fig. 1) and the 12 mth running total SOI. The extreme variability of rainfall and the frequent drought periods are obvious. seen. Table 2 shows the significant recorded droughts (rainfall percentile <10%) for 12 mth and 30 mth rainfall totals identified as the period below 40 percentile rainfalls.

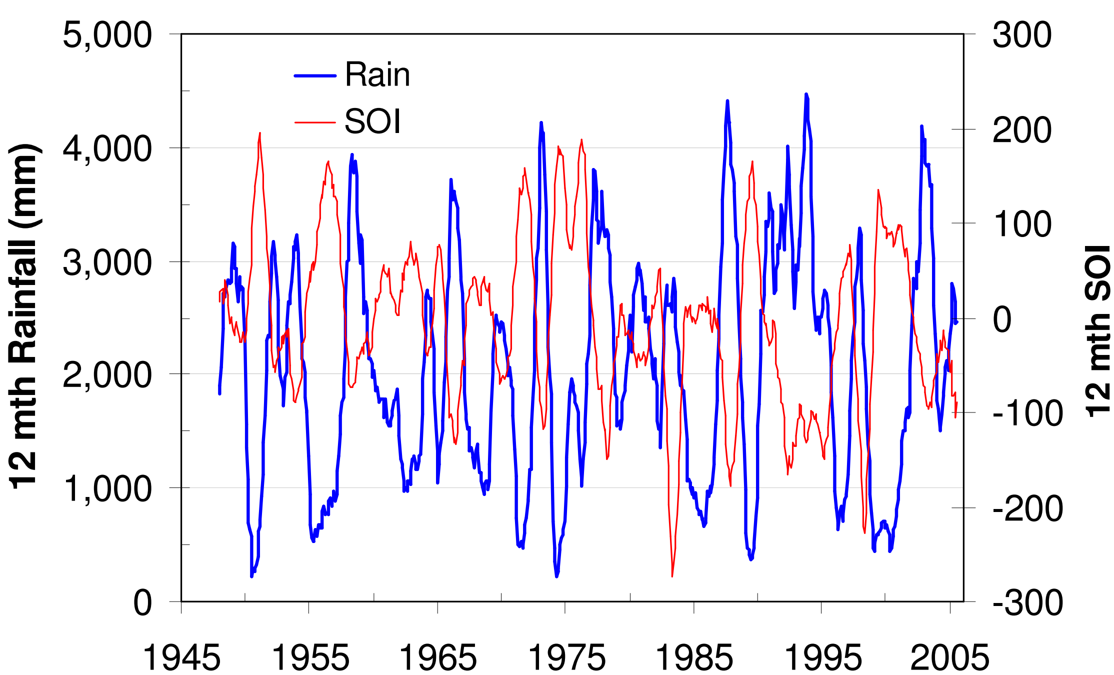

Fig. 3. Relationship between 12 mth running total rainfall and 12 mth running total SOI for Betio, Tarawa atoll, Kiribati

Table 2 Significant droughts in Tarawa for 12 and 30 mth rainfall totals.

12 mth Rainfall				30 mth Rainfall			
Start Date (<40%)	**End Date (>40%)**	**Duration (mths)**	**Lowest Percentile**	**Start Date (<40%)**	**End Date (>40%)**	**Duration (mths)**	**Lowest Percentile**
Jan-50	Aug-51	19	0.1	Aug-55	Feb-58	30	1.3
Oct-54	Aug-57	34	4.4	Mar-71	Jun-73	27	9.5
Dec-70	Jun-72	18	2.7	Nov-74	Nov-76	24	4.6
Dec-73	Apr-75	16	0.0	Jan-85	Apr-87	27	3.4
May-84	Oct-86	29	9.1	Nov-98	Jun-02	43	0
Oct-88	Mar-90	17	1.3				
Nov-95	Apr-97	17	7.6				
Jul-98	Dec-01	41	2.0				
	Mean	24			**Mean**	30	

It has been shown that 12 mth rainfall percentiles are relevant to domestic wells in islands with thinner freshwater lenses, while 30 mth percentiles are more relevant to islands with thicker lenses (White *et al.*, 1999a). While the Dec 1973 to Apr 1975 drought recorded the lowest 12 mth rainfall amounts on record, the more recent, Nov 1998 to Jun 2002, drought was the most severe for islands with larger freshwater lenses. With the definition of the start (rainfall less than 40 percentile) and end of the drought (rainfall returns to greater than 40 percentile), the average duration of droughts (rainfall <10 percentile) for the 12 mth rainfall totals is 24 months while that for 30 mth totals is 30 mths. The 1998-2001 drought is the longest on record for both rainfall periods. During this drought, almost all raintanks were exhausted, many domestic wells became saline and saline groundwater caused the death or severe die-back of mature (40 year old) breadfruit trees

Groundwater

To a first approximation, the maximum thickness of a freshwater lens, from which water is being pumped, to an assumed sharp interface between fresh and saltwater, H_p (m) is given by the steady state expression (Volker et al., 1985):

$$H_p = \frac{(1-q)^{1/2} W}{2}\left((1+\alpha)\frac{.R}{2K_0}\right)^{1/2} = (1-q)^{1/2} H_u \qquad [1]$$

where W is the width of the atoll, q the ratio of pumping rate to recharge rate, $q = (Q/A)/R$,

Q/A (mm) is the annual pumping rate per unit area (A), R (mm) is the net groundwater recharge rate, $\alpha = (\rho_s - \rho_0)/\rho_0$ where ρ_s, ρ_0 are the densities (t/m^3) of sea and freshwater, K_0 is the hydraulic conductivity, (m/y), of freshwater in the Holocene sediments in the horizontal direction and H_u is the thickness of the unpumped groundwater lens. For Bonriki, the estimated mean groundwater thickness in the absence of pumping is about 15 m.

Eqn [1] can be used to estimate impacts of long term drought on the thickness of the freshwater lens to an assumed sharp interface. The ratio of the freshwater lens thickness during prolonged drought, H_d to the long term mean freshwater thickness H_m, regardless of whether there is pumping or not, follows from eqn [1]:

$$H_d = (R_d / R_m)^{1/2} . H_m \qquad [2]$$

where R_d and R_m are the long term recharges under drought and mean conditions. If we assume that during long term drought the long-term recharge falls from 980 to about 200 mm/year, then eqn [2] predicts that the thickness of the freshwater lens will be reduced to only about 50% of its long term mean. This figure is consistent with measurements at Bonriki during the 1998-2001 drought. This 50% reduction in lens thickness suggests that the watertable elevation could fall by about 400 mm from its long-term mean value during a prolonged drought.

A comparison of the measured watertable elevation in boreholes across Bonriki at the end of the 1998 to 2001 drought with those in more recent, wetter times is given in Table 3. This shows that the mean watertable elevation was at least 440 mm lower during the extended 1998 to 2001 drought than in wetter periods.

Table 3. Measured change in mean watertable elevation due to drought, Bonriki.

Measurement date	Mean watertable elevation above arbitrary datum (mm)
3-4 November 2001	190
27-28 February 2003	630
Difference	**-440**

Fig 4 shows the change in freshwater depth during wet and dry periods in the groundwater lens on Bonriki island (Fig 2), in a salinity borehole at the seaward edge of the island, to the 12 mth rainfall deciles. The edge of this thick freshwater lens responds dramatically to long dry periods. Boreholes towards the centre of the island showed relatively smaller decreases in the thickness of the freshwater lens, which in the centre is over 20 m thick.

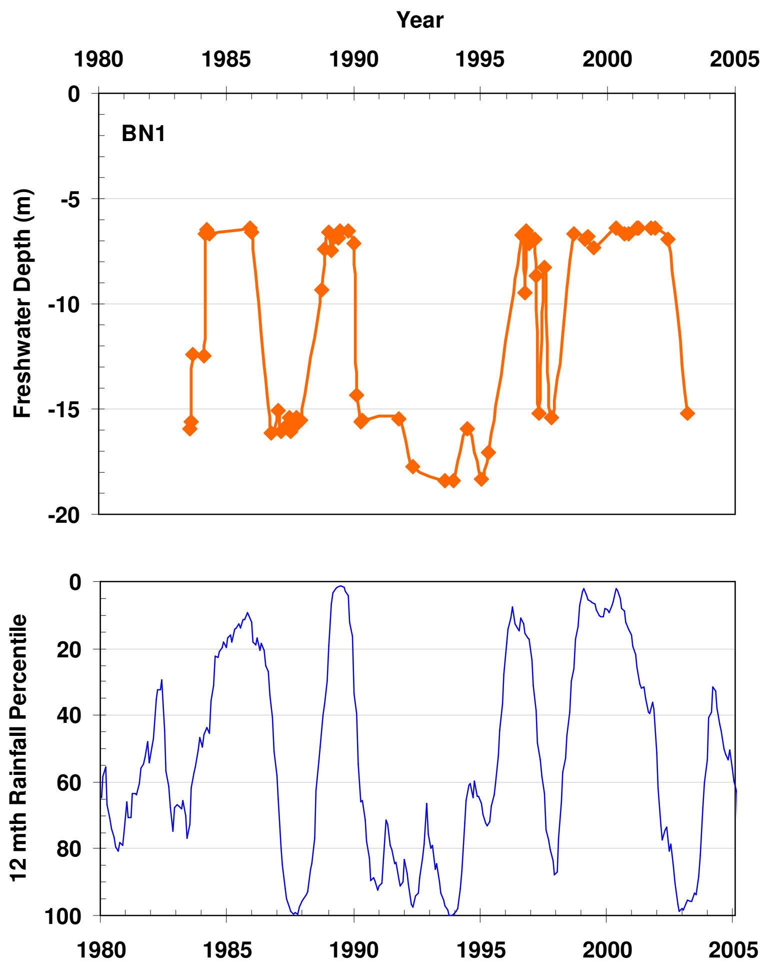

Fig. 4 Change in depth below ground surface of the freshwater/salinity transition zone for a salinity borehole (BN1) at the ocean edge of Bonriki island, Tarawa atoll and its relation to 12 mth rainfall percentiles.

As the lens thin during dry periods, the salinity of the fresh groundwater also increases. Fig 5 shows the increase in groundwater salinity (electrical conductivity, EC) of groundwater pumped from both Buota and Bonriki groundwater reserves during the severe 1998-2001 drought. Even though the EC peaked at around 1,000 µS/cm at the end of 2001, the water was still quite acceptable for domestic use. Since this was the worst drought on record for 30 mth rainfalls, this illustrates the robustness of large freshwater lenses in islands that are of widths approaching 1 km.

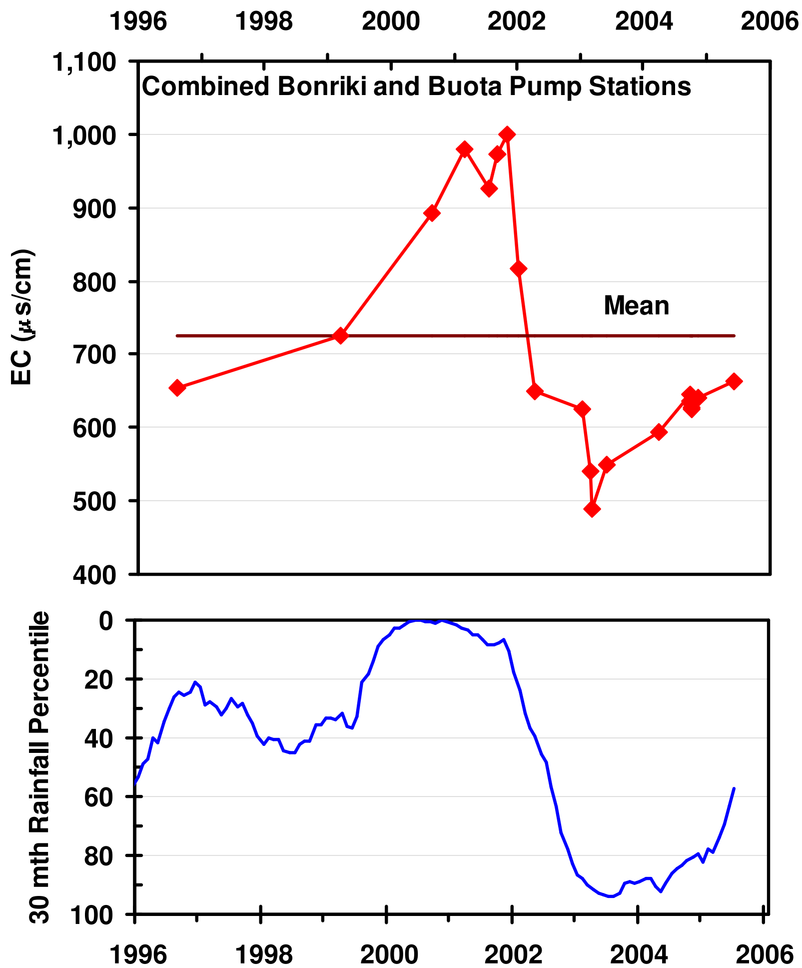

Fig. 5 Impact of the 1998-2001 drought on the groundwater salinity (EC) of combined waters pumped from the freshwater lenses in Buota and Bonriki islands (Fig 1).

The impacts shown in Fig 4 and 5 may not be due to just climate alone, since groundwater is also extracted from these islands at combined rates approaching 1,700 m^3/day. The impact of pumping on the freshwater lenses will now be considered.

IMPACT OF PUMPING ON GROUNDWATER ELEVATION AND THICKNESS

Traditional land owners in islands used as groundwater sources for freshwater reticulation are concerned over the impacts of groundwater pumping on the health and productivity of traditional crops (White *et al.,* 1999b). These concerns have centred on the effects of pumping on lowering unconfined watertables so that taro crops are unproductive or coconut yields are reduced. Pumping in existing fresh groundwater extraction reserves has also been blamed for the unhealthy appearance or death of coconut trees and increasingly brackish domestic wells, possibly through an increase in the salinity of the groundwater. Coconut trees have an unusually high requirement for chlorine and can tolerate a moderate amount of salinity in groundwater provided the saline watertable fluctuates with the tide or is sufficiently deep. However, while they can withstand brief exposures to seawater, permanent exposure to water with salinity of 2000 mg/L TDS or greater (EC above 2,800 μS/cm) severely retards growth (Foale, 2003).

The annual water balance for a freshwater lens in a low coral atoll in which extraction by pumping is taking place (see Fig. 1) is given by (Falkland, 1992):

$$R = GF + D + Q/A + \Delta S \qquad [3]$$

where *GF* (mm) is the groundwater discharge to the sea and lagoon, *D* (mm) is the mixing or dispersion losses at the base of the lens, and Δ*S* (mm) is the change of freshwater volume per unit area stored in the lens (positive when recharge is greater than the losses, negative when recharge is less than the losses). In the long term, Δ*S* is negligible and recharge equals losses,

$$R = GF + D + Q/A \qquad [4]$$

Estimated mean annual components of the water balance in eqn [4] for Bonriki are given in Table 4. In Table 4, the evapotranspiration component is the water used by vegetation. We have assumed here that this component is unchanged by pumping (White *et al.*, 2002). Eqn [1] suggests that the average mean groundwater thickness of the freshwater lens during pumping at the rate given in Table 1 should be about 10.9m. If h_0 is the height of the watertable above mean sea level ($h_0 = H_u \alpha/(1+\alpha)$), then, during pumping, the average watertable elevation should drop by about 140 mm (Table 1).

Table 4 Principal components of the annual water balance for Bonriki Island.

Component	Estimated depth (mm)	Estimated volume* (m^3)
Mean Rainfall, P	2,000	2.80×10^6
Mean Actual Evapotranspiration, ET	1,020	1.43×10^6
Mean Net Recharge, R	980	1.37×10^6
Before Groundwater Pumping		
Mean Outflow & Dispersion, GF+D	980	1.37×10^6
Mean Fresh Groundwater Thickness	15,000	$6.3 \times 10^{6\dagger}$
Mean Watertable Height above MSL#	700	-
After Groundwater Pumping		
Sustainable Pumping Yield, Q	352	$0.49 \times 10^{6\ddagger}$
Mean Outflow & Dispersion, GF+D	628	0.88×10^6
Mean Fresh Groundwater Thickness	12,000	5.04×10^6
Approx. Mean Watertable ht above MSL#	560	-
Approx. Max. Change in Watertable#	**140**	-

* Based on the estimated area of Bonriki island of 140 ha
† Based on an estimated specific yield of 0.3
‡ Based on the current estimated sustainable yield of 1,350 m^3/day (Alam *et al.*, 2002)
\# At the centre of the island.

Fig. 6 shows that the watertable in Bonriki gallery pump stations fluctuates twice daily in concert with the tidal signal from the Betio tide gauge recorder. This daily fluctuation is caused by the tidal pressure signal transmitted mainly through the karstic Pleistocene limestone aquifer beneath the freshwater lens (Wheatcraft and Buddemeier 1981, Oberdorfer *et al.*, 1990) and transmitted upwards to the groundwater surface. The results for the watertable in the Bonriki gallery pump station PS 16 show a twice-daily change of up to 170 mm in watertable elevation can be generated by the tidal cycle. In other galleries, tidal amplitudes of up to 300 mm have been measured in the watertable elevation. The impacts of rainfall on watertable elevation is also shown in Fig. 6 where it can be seen that rapid rises as high as 0.65 m can occur during rainfall.

Table 5 compares the magnitude of changes in the watertable elevation in the Bonriki freshwater lens produced by natural processes, long term drought, rainfall and diurnal tidal fluctuations, with the change due to continued pumping. We conclude that the change due to pumping is smaller than changes due to natural processes and that pumping from horizontal infiltration galleries should have a negligible effect on traditional crops such as coconuts and swamp taro.

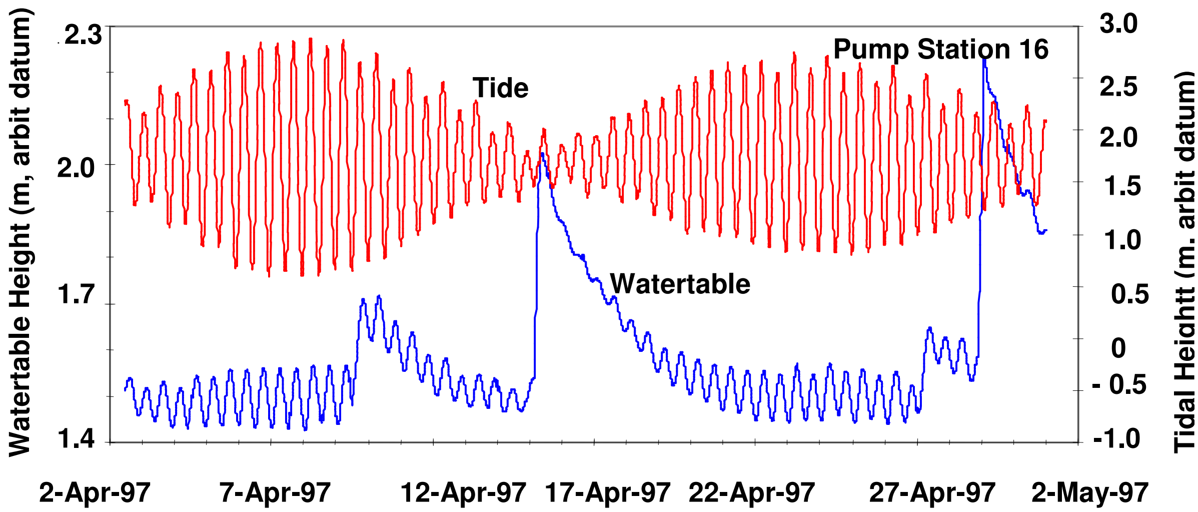

Fig. 6 Influence of the tidal cycle on watertable elevation in a Bonriki infiltration pump station (PS 16).

Table 5 Maximum observed changes in watertable elevation at Bonriki due to natural processes compared to that estimated from pumping.

Process	Maximum change in water table elevation (mm)
Natural	
Major Rainfall Events	650
Diurnal Tidal Forcing	300
Prolonged Drought	440 (Table 3)
Pumping	
Estimated max decrease	140 (Table 4)

DRAWDOWN DUE TO INFILTRATION GALLERY PUMPING STATIONS

To a first approximation, the maximum unconfined watertable draw down, δ (m), for an individual infiltration gallery pumping at a rate Q can be found by integrating Darcy's law:

$$\delta = W_G\, Q/\left(8 K_0 H_u L_G\right) \qquad [5]$$

where W_G (m) is the width of the gallery extraction zone and L_G is the length of the gallery. Typically values for the pumping galleries in Bonriki (Fig 2) are L_G = 300 m, W_G = 100 m, H_u = 15 m. Hydraulic conductivities of the unconsolidated Holocene coral sediments vary between about 5 and 50 m/day and individual pumping rates vary from about 40 to 140 m^3/day. The estimated drawdown using these typical values in eqn [5] is expected in the range of about 2 mm to 80 mm.

Pump drawdowns were measured by switching pumps off and then on again in 16 infiltration gallery pumping stations in Bonriki (Fig 2) and following the change in watertable elevation with a pressure transducer. A typical measurement is shown in Fig 7. The mean pumping rate for the galleries was 96 ± 27 m^3/d and the mean measured draw down was 33 ± 46 mm, with a maximum measured drawdown of 200 mm and a minimum of 2 mm. This clearly indicates that groundwater pumping drawdown has an insignificant impact on traditional crops. Using these measurements in eqn [5], the estimated mean hydraulic conductivity of the Holocene coral sediments is 8.1 m/day.

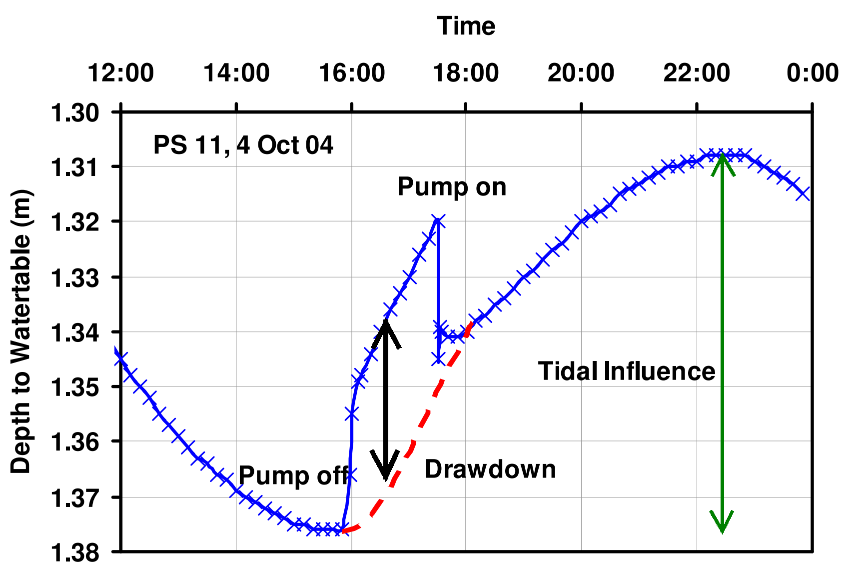

Fig.7 Pressure transducer record of drawdown tests showing the impact of switching the pump on and off on the depth to the watertable in an infiltration gallery pumping station on Bonriki.

IMPACTS OF LANDUSE ON WATER QUALITY

In low coral atolls, the watertable is close to the soil surface and superficial contaminants are rapidly translocated into the groundwater. Traditional practices, in low-density populations, have evolved to minimise contamination risk. These include defecation on beaches down gradient from recharge areas, sweeping leaves and debris away from dwellings and domestic wells and keeping pigs on the lagoon side of islands, in groundwater discharge zones. Increasing population is placing significant strains on natural resources, particularly land and water, and has generated tensions between the traditional values and practices of subsistence communities and the demands of an urbanised societies (White *et al.,* 1999; Perez *et al.*, 2004). An important issue in atolls is the impacts of animal wastes, particularly from pigs, on drinking water. In Kiribati there are an estimated 0.32 pigs/person (Saville and Manueli, 2002).

In some large islands used as groundwater sources for reticulation systems, one strategy has been for governments to declare lands overlying groundwater sources to be water reserves and to restrict land uses. Land ownership and use, however, is central to existence in most island communities (Jones, 1997). Declaration of reserves is therefore problematic for the affected landowners, whose landuses and rights are restricted. In some cases, declarations have generated long lasting disputes and have resulted in vandalism of water infrastructure (White *et al.*, 1999). A critical question raised in disputes between landowners and governments concerns the type of landuses that are acceptable in groundwater source areas. With land area severely limited there are significant pressures to maximise land use especially in agricultural production.

Bonriki water reserve (Fig 2) has been encroached on by squatters who have established market gardens and have pig pens on the water reserve. Water quality testing for the presence of faecal contamination using *E. coli*, and for concentrations of dissolved organic carbon, DOC, total dissolved nitrogen, TDN, and nitrate and phosphate was carried out on all infiltration gallery pump stations in Bonriki (Fig 2). The results for *E. coli* are shown in Fig 8. . There are extensive, abandoned taro pits, squatter dwellings pig pens, a cemetery and extensive market gardens in the vicinity of the positive galleries. Similar results were found for the other nutrients tested. Ratios of carbon to nitrogen in groundwaters indicated the presence of both microorganisms and added nitrogen.

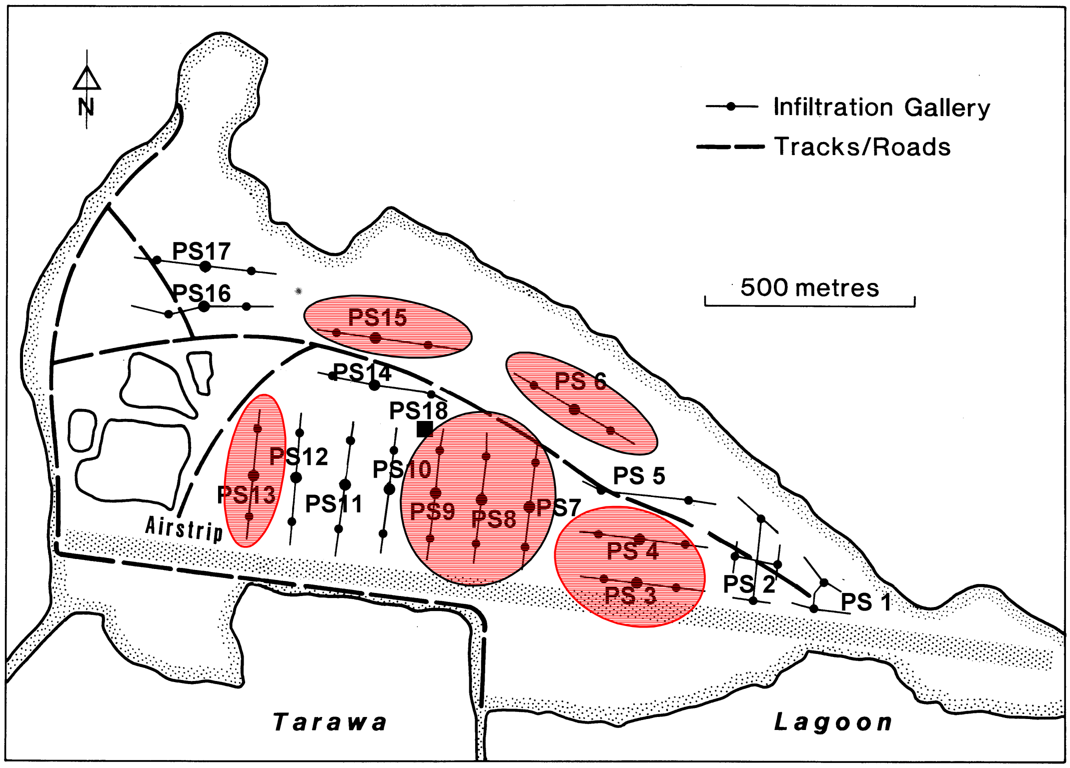

Fig. 8 Distribution of positive *E. Coli* water samples from pumping galleries on Bonriki.

ADAPTATION STRATEGIES TO DECREASE RISK AND INCREASE RESILIENCE

Locations, such as Tarawa atoll, where demand for water matches or exceeds available water supplies are very vulnerable to climate variations and increasing population pressures. Available adaptation strategies for reducing risks and increasing resilience are limited but a key factor is the provision of appropriate knowledge. In many small islands, meteorological services and water supply agencies are under-resourced and their ability to predict water-related extreme events is limited. The actual amount of water that is available for use and its quality are largely unknown, particularly in outer islands. Monitoring and analysis are also at best spasmodic. As well, there has been a general reluctance to enact national water legislation, defining rights, policies and responsibilities and to involve communities in managing and planning water and related land resources.

Proposed adaptation strategies for small islands can be grouped proposed under 3 main themes, *capacity strengthening*, *demand management and refurbishment, protection and supplementation of freshwater resources* (Falkland, 2005). Within these themes, at least ten strategies could help increase the resilience of small island communities to water–related climate and human changes (White, 2005):

1. Establish a sound institutional basis for the management of water and sanitation (policy, regulations, incentives, plans, organisational reform and assignment of responsibilities).
2. Improve community participation in water and related land management and planning and reduce conflicts.
3. Increase capacity to manage water and sanitation at the household and community levels.
4. Increase capacity to analyse and predict water-related extreme events.
5. Improve knowledge of available water resources, their quality and demand for them.
6. Improve water conservation and demand management strategies and reduce leakages.
7. Increase household and communal rainwater harvesting and storage.
8. Protect groundwater source areas from contamination.
9. Increase the use of groundwater.
10. Improve sanitation systems to minimise water use and pollution.

Australia is currently initiating work to help small island countries in the Pacific implement these strategies in through its Pacific Vulnerability and Adaptation Project.

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